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Entangling superconductivity and antiferromagnetism

Subir Sachdev

Department of Physics, Harvard University, Cambridge MA 02138, USA

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Today we have two families of high transition temperature (T_c) superconductors, based respectively upon compounds in which copper and iron atoms occupy layered square lattice. Many physicists have intensively studied the question of how the quantum mechanics of electrons moving co-operatively on such lattices can lead to high-T_c superconductivity. A common feature of both families of high-T_c superconductors is that also display an interesting form of magnetism, known as "antiferromagnetism", as their chemical compositions are varied (see the figure). The interplay between these magnetic and electric properties, antiferromagnetism and superconductivity respectively, is thought by many to be controlled by intricate quantum entanglement among the electrons, and to be at the origin of the fascinating properties of these materials. The antiferromagnetism is invariably strongest at compositions at which the superconducting T_c is either zero or quite small. As the composition is varied and the antiferromagnetism decreases, we reach a special critical composition at which the antiferromagnetism first vanishes at zero temperature, an example of a *quantum* phase transition. In this issue of Science, Hashimoto *et al.* report [1] striking observations at an especially well characterized example of such a quantum critical point in a high-T_c superconductor, crystals of $BaFe_2(As_{1-x}P_x)_2$ with minimal chemical disorder. A novel feature of their experiments is that the signature of a magnetic critical point is observed in an electrical property: the antiferromagnetic quantum critical point leads to a singular change in the ability of the electrons to carry current without dissipation (a 'supercurrent'). This experiment demonstrates the close connection between antiferromagnetism and high-T_c superconductivity.

Low temperature superconductors like mercury are now well understood by the 1957 theory of Bardeen, Cooper, and Schrieffer (BCS). A key feature of their theory is that pairs of electrons bind to form particles known as Cooper pairs, which are bosons. These bosons can then undergo condensation into a common quantum state, similar to that in the Bose-Einstein theory, and this explains much of the phenomenology of the traditional superconductors. The pair-binding of the electrons requires an attractive potential between them, and this appears when the electrons exchange quanta of lattice vibrations.

Extending this picture to the high-T_c superconductors requires a stronger attractive potential, stronger than the lattice vibrations can provide. One possible source is the antiferromagnetism: the electrons can exchange quanta of the 'vibrations' of the local antiferromagnetic order, which is linked to fluctuations of the electronic spin. Provided the coupling constant of this exchange process is small, a reliable theory of superconductivity can be developed using the BCS framework. One of the predictions of such a theory [2] is that the Cooper pairs that form via this mechanism must have a wavefunction which changes sign when the momenta of their constituent electrons are moved through the range of possible values (in the copper-based high-T_c superconductors, such Cooper pairs have a "*d*-wave" symmetry) — see the figure. And indeed just such a sign change has been observed in both classes of high-T_c superconductors [3, 4].

However, such a BCS theory cannot completely explain high-T_c superconductivity, because it is only valid when the coupling constant is small. Can we not assume that larger coupling constants will lead to the needed high T_c's, and so declare that the physics has at least been qualitatively understood? The answer is no: increasing the coupling constants leads to several new effects which are not included in the BCS theory, some of which are detrimental to superconductivity.

One method of turning up the coupling strength is to approach the antiferromagnetic quantum critical point [5]. Here the attraction does indeed increase, and, moreover, beyond-BCS effects can be systematically studied. The stronger coupling leads to strong scattering in which the electrons lose most of their energy to the quanta of the collective antiferromagnetic fluctuations, and the electron-like particles of the metal become heavier, and some of them lose their integrity [6]; this is detrimental to superconductivity because it is these very particles which are the constituents of Cooper pairs. Should some of the electrons form Cooper pairs anyway, the resulting modification of the Fermi surface of the metal (see the figure) can suppress antiferromagnetic fluctuations needed for the pairing of the remaining electrons. And finally, other types of ordering can appear as bi-products of the stronger coupling, such as the formation of 'stripes'. Recent work [7] has argued that the Cooper pair formation nevertheless remains the dominant consequence of the strong-coupling of the electrons to antiferromagnetic spin fluctuations at the critical point, and that high-T_c superconductivity is the most likely consequence.

The observations of Hashimoto *et al.* [1] show a clear new signature of this tug-of-war between antiferromagnetism and superconductivity. The value of T_c is a maximum close to the antiferromagnetic quantum critical point, signaling that antiferromagnetic quantum critical fluctuations do indeed enhance Cooper pair formation. On the other hand, their measurements of the length a magnetic field can penetrate the superconductor (the "London penetration depth") at zero temperature, show, surprisingly, that this length is also a maximum at the quantum critical point. A larger penetration depth implies, via the London equations, that the ability of the electrons to a carry a supercurrent is actually at a *minimum* at the quantum critical point. One possible explanation is that the electrons, and so the Cooper pairs, have an average effective mass which is larger at the critical point, and this impedes their motion. Such an enhancement in the mass of the electrons is a natural consequences of the strong scattering by the antiferromagnetic spin fluctuations. Thus the maximum in T_c, and the concomitant maximum in the penetration depth, constitute remarkable evidence for the opposing tendencies in the influence of the antiferromagnetic quantum critical point on high-T_c superconductivity. These observations will surely be valuable in the ongoing theoretical effort to unravel the quantum interplay between antiferromagnetism and superconductivity.

[1] K. Hashimoto *et al.*, "A sharp peak of the zero-temperature penetration depth at optimal composition in the iron-based superconductor $BaFe_2(As_{1-x}P_x)_2$", preprint (2012).

[2] A. V. Chubukov, Annual Reviews of Condensed Matter Physics **3**, 57 (2012).

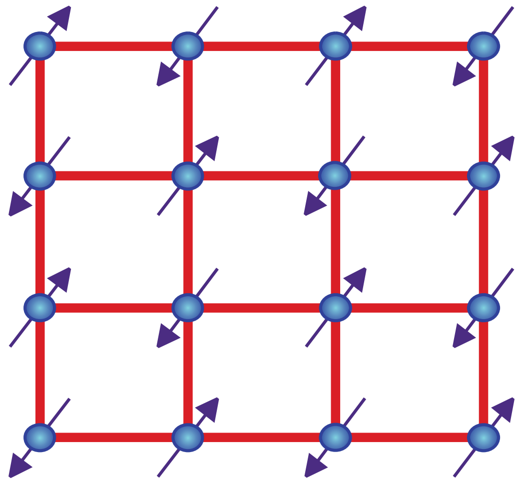
[3] C. C. Tsuei, J. R. Kirtley, C. C. Chi, Lock See Yu-Jahnes, A. Gupta, T. Shaw, J. Z. Sun, and M. B. Ketchen Phys. Rev. Lett. **73**, 593 (1994).

[4] T. Hanaguri, S. Niitaka, K. Kuroki, and H. Takagi, Science **328**, 474 (2010).

[5] Ar. Abanov, A. V. Chubukov, and A. M. Finkel'stein, Europhys. Lett. **54**, 488 (2001).

[6] A. J. Millis, Phys. Rev. B **45**, 13047 (1992).

[7] M. A. Metlitski and S. Sachdev, Phys. Rev. B **85**, 075127 (2010).



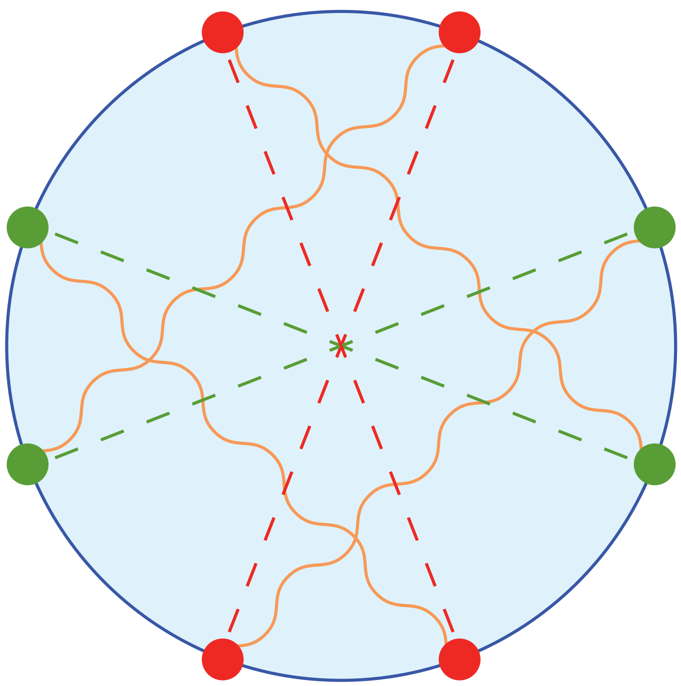


FIG. 1. The top figure shows the antiferromagnetism on the square lattice of Cu ions in a high-T_c superconductor. The arrows indicate the orientation of the electron spins. In a ferromagnet all electrons spins are parallel, while in an antiferromagnet they oscillate in space, as in the checkboard pattern shown here. The big shaded blue circle is a picture of the occupied electron states in the momentum space of a metal; its boundary is the Fermi surface. Eight particular single electron states on the Fermi surface are indicated by the small circles. The wavy lines connect electrons which can scatter into each other via exchange of a quantum of an antiferromagnetic spin fluctuation. The dashed lines connect electrons which form Cooper pairs. The Cooper pairs of the red circles have a wavefunction with the opposite sign from the green circles, a characteristic feature of superconductivity mediated by antiferromagnetism. Note that the wavy lines only connect circles with different colors.